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Free-standing planar thin-film thermoelectric microrefrigerators and the effects of thermal and electrical contact resistances

Yu Su [a], Jianbiao Lu [a], Baoling Huang [a,b,*]

[a] Department of Mechanical and Aerospace Engineering, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong
[b] The Hong Kong University of Science and Technology Shenzhen Research Institute, Shenzhen, China

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ABSTRACT

Thermoelectric microrefrigerators provide an attractive solid-state solution for on-chip thermal management of microelectronics due to their unique advantages. Here we propose a free-standing planar design of thermoelectric microrefrigerator based on thin film technologies to address the high-performance on-chip cooling and compatibility with microelectronics fabrication. By combining theoretical modeling, numerical simulations and experiments, we conducted a comprehensive investigation of the steady-state and transient performances of the proposed microrefrigerators and various factors that might influence their performance, such as contact resistances, element geometries, convection and radiation, have been explored. Both thermal and contact resistances are found to be important for the cooling performance of the proposed microrefrigerators while they play different roles on the cold and hot sides of a refrigerator. The influence of contact resistances on the design strategies of a microrefrigerator is also discussed. It is demonstrated that microrefrigerators based on IC-compatible low-cost SiGe thin films can potentially achieve a cooling temperature more than 20 K with a response time shorter than 40 ms near room temperature, rendering them competitive against the state-of-the-art microrefrigerators based on toxic conventional heavy metal thermoelectrics such as Bi_2Te_3 and Sb_2Te_3.

1. Introduction

The rapid development of microelectronic devices along with the significant shrinkage in feature size has resulted in a sharp increase in device power density and junction temperature, leading to great challenges in the thermal management. Among various cooling techniques, thermoelectric (TE) cooling is quite attractive due to its all-solid-state nature, high reliability, long lifetime, and fast response [1–6]. It is also one of the few techniques that can be easily scaled down to micro domain and keep the device temperature well below the ambient temperature, which is crucial for the on-chip refrigeration of micro devices requiring a low working temperature [6–8]. To achieve on-chip refrigeration, thin film technologies have been widely used due to their capability of miniaturizing TE elements and excellent compatibility with standard integrated circuit (IC) fabrication processes. Conventional macro TE refrigerators usually adopt a vertical design (Fig. 1(a)), in which the TE elements (or heat flow) are perpendicular to the substrate. However, the top/bottom contacts will seriously deteriorate the cooling performance when the device is downscaled to micro level[9–11]. In contrast, relatively long TE elements can be easily fabricated from thin films using the planar structure (Fig. 1 (b)), in which TE elements lie on the substrate surface and the heat flow is parallel to the substrate. Since TE elements may have a large contact area with the electrodes in the planar configuration, the challenge in obtaining low contact resistance may be alleviated. Therefore, the planar structure may be more suitable for integrated micro refrigeration.

Great efforts have been made in the past decades to build up the models to study thermoelectric modules [2,12–17] and develop high-performance TE planar refrigerators [10,11,18,19]. The performance of these TE micro refrigerators essentially depends on the figure of merit $ZT = \alpha^2 T/(\rho\ k)$ of the TE material being used, where α is the Seebeck coefficient, ρ is the electrical resistivity and k is the thermal conductivity of the material. Currently, Te-based heavy metals or alloys (e.g., Bi_2Te_3 and Sb_2Te_3) are widely used in micro TE modules due to their high ZT (around 1.0) near room temperature [9,10,19–22]. These Te-based thin films are generally quite fragile and a supporting layer is always needed to enhance the mechanical strength (Fig. 1(c)); however, the corresponding parasitic heat loss will seriously suppress the cooling performance of the TE microrefrigerators [11,23]. Besides,

* Corresponding author at: Department of Mechanical and Aerospace Engineering, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong.

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Nomenclature

A	contact area
A_c	surface area of the central island
A_{te}	surface area of the TE leg
COP	coefficient of performance
h	heat transfer coefficient for convection
H_{eff}	effective heat transfer coefficient
I	input current of the TE refrigerator
J	current density
k	thermal conductivity
K_{eff}	effective thermal conductance
K_{te}	thermal conductance of the TE leg
L	length of the TE leg
n	number of TE legs
q	heat flux
Q	cooling capacity
r_c	electrical contact resistivity
r_{ct}	thermal contact resistivity
R_{cc}	cold side electrical contact resistance
R_{ch}	hot side electrical contact resistance
R_{cct}	cold side thermal contact resistance
R_{cht}	hot side thermal contact resistance
R_{te}	electrical resistance of the TE leg
t	thickness of the TE thin film
T_{ave}	average temperature of the TE leg
T_c	cold region temperature of the TE refrigerator
T_{c0}	cold side temperature of the TE leg
T_h	hot region temperature of the TE refrigerator
T_{h0}	hot side temperature of the TE leg
w	width of the TE leg
Z	figure of merit
Z'	effective figure of merit

Greek symbols

α	seebeck coefficient
ε_{te}	emissivity of the TE leg
ε_c	emissivity of central island
σ	Stefan-Boltzmann constant
ρ	electrical resistivity
ΔT	cooling temperature difference

Subscripts

i	stage number
in	input
max	maximum value
opt	optimized condition
out	output

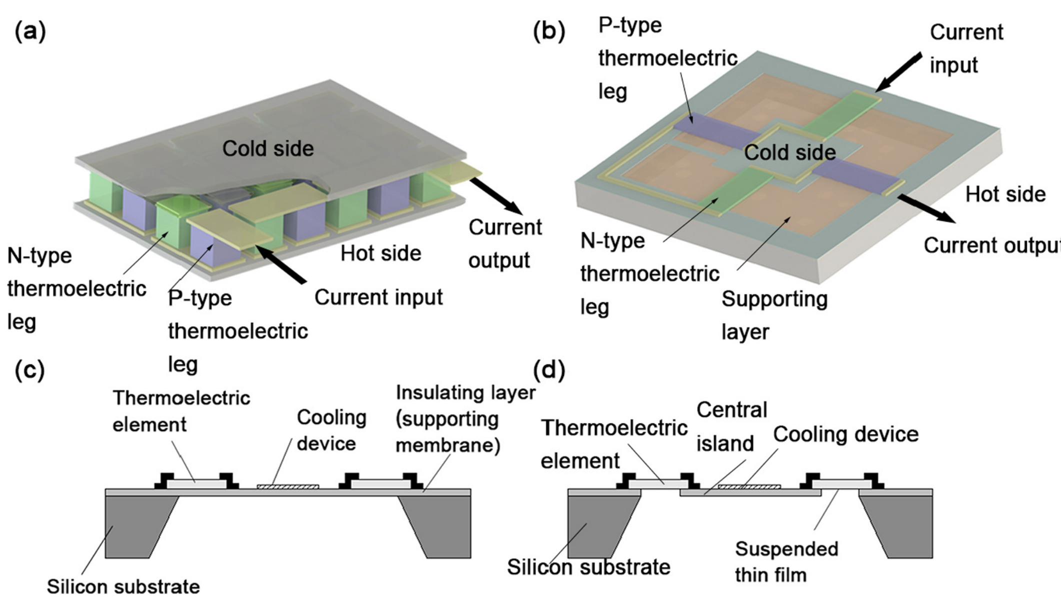

Fig. 1. (a) Conventional vertical design. (b) Conventional planar design. (c) Schematic of a planar TE refrigerator with a supporting membrane. (d) Schematic of a free-standing planar TE refrigerator.

Bi_2Te_3/Sb_2Te_3 often have poor electric contacts with metals due to the formation of interfacial compounds [24]. Gross et al. [13] showed that the effective device *ZT* of a planar micro refrigerator comprising Bi_2Te_3/Sb_2Te_3 elements of a *ZT* around 0.4 could be reduced to 0.02 due to the parasitic heat loss and large electric contact resistance. It is a natural idea to adopt TE materials of high mechanical strength such as SiGe and construct a free-standing structure, as shown in Fig. 1(d), to eliminate the parasitic heat loss. So far, however, there are few experimental or theoretical researches on free-standing planar micro refrigerators. This is probably due to the lack of TE thin films with both a high *ZT* and good mechanical strength, e.g., the reported *ZT* values of SiGe thin films are often below 0.04 near room temperature.

Nevertheless, recently Lu et al. [25] reported that the room-temperature *ZT* value of nanograined SiGe thin films deposited by low-pressure chemical vapor deposition can reach up to 0.2, higher than the effective *ZTs* of many Bi_2Te_3/Sb_2Te_3 –based thin film microrefrigerators. SiGe also offers low toxity, high contact conductivity with metal (generally 10^8 to 10^{12} S/m^2) and good compatibility with standard microelectronic fabrication processes, making it promising to develop free-standing thin film planar TE microrefrigerators. It is desirable to explore the cooling behavior